# VIGIL – a GPS based target-tracking system

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## ABSTRACT

The VIGILANTE project is a planned vision system capable of tracking and recognizing targets in real time, on a small airborne platform. The project consists of two parts, 1) the Viewing Imager/Gimballed Instrumentation Laboratory (VIGIL), which is an infrared and visible sensor platform with appropriate optics and 2) the Analog Neural Three-dimensional processing Experiment (ANTE), a massive parallel, neural based, high-speed processor.

The VIGIL platform is mounted on a helicopter equipped with Global Position System (GPS), Inertia Measurement Unit (IMU), gimbal, radio-link and anti-vibration platform. Also, a jet powered, radio controlled VIGILANTE Target Vehicle (VTV) has been manufactured and equipped with GPS. In the first stages of the project, the VIGIL system is used to acquire image sequences of the VTV for training and testing of the ANTE image recognition processor. Based on GPS and IMU input, the gimbal is pointed toward the VTV and acquires images.

This paper describes the VIGIL system in detail. It discusses position-based pointing and tracking algorithms and the alignment procedure. Test imagery and an evaluation of the system will be presented.

**Keywords:** GPS based tracking, GPS based pointing, VIGILANTE, Airborne sensor.

## 1. INTRODUCTION

Small air and space borne systems capable of autonomous acquisition and identification of hostile targets (e.g., cruise missiles, missile launchers etc.) will become an essential component of the Ballistic Missile Defense Organization's (BMDO) planned defensive mechanisms. Such Automatic Target Recognition (ATR) capability could greatly increase the capabilities of interceptors (for cruise and ballistic missiles), surveillance platforms (for missile launchers), and ground-based fire control.

The VIGILANTE project at Jet Propulsion Laboratory (JPL) [1] provides a low-cost airborne platform that combines new sensors with advanced neural network processing algorithms for detection, recognition and tracking of missile threats. The project consists of two parts, the airborne VIGIL platform and the ANTE ATR processor.

VIGIL (Viewing Imager/Gimballed Instrumentation Laboratory) is a helicopter-based gimballed camera platform providing data acquisition for target training/recognition experiments as well as testing of novel active and passive focal plane imagers. VIGIL provides realistic image conditions for airborne targets seen from above. To point the sensors toward the target (before the ANTE ATR becomes operational), both the helicopter and VTV are equipped with GPS receivers, to provide the pointing information. ANTE (Analog Neural Three-dimensional processing Experiment) is a prototype image-processing/target-recognition computer architecture based upon technology developed under the ongoing 3 dimensional artificial neural network (3DANN) program. 3DANN is a sugar-cube-sized, low-power neural processor. It is capable of

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performing 64 simultaneous image convolutions with 64x64-kernel size in real time [2] - [6]. This system will not be described further in this paper.

This paper describes VIGIL in detail. The algorithms for pointing the cameras towards the VTV are described. Also, the alignment procedures and noise sources are discussed.

## 2. DESCRIPTION OF THE VIGIL SYSTEM

The VIGIL system consists of an airborne helicopter equipped with the gimbal sensor platform and a jet-powered target called the VTV.

The VTV: A re-useable, remote controlled target vehicle supports testing of VIGILANTE. Field testing of actual target signatures and backgrounds provides realistic scenarios needed to train and evaluate the ANTE system and its associated ATR algorithms. The VTV resembles a cruise missile, but is flown as a remote-controlled aircraft. An infrared signature is obtained from a Turbomin turbine engine producing 22 pounds of thrust for a flight time of about 15 minutes. The VTV is depicted in figure 1. It is 2.42 meters long, has a 1.18 meter wingspan and a mass of 17 kilos.
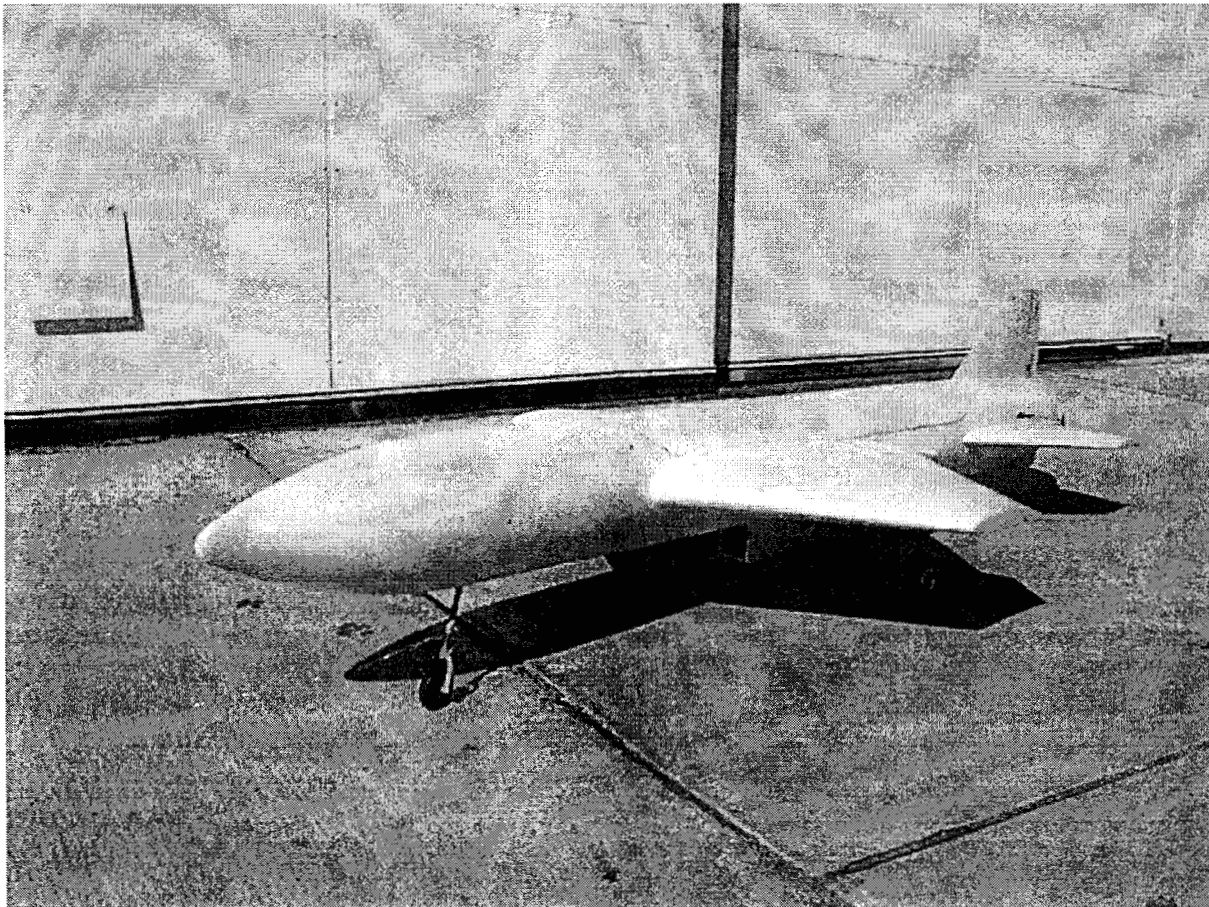


**Figure 1. The VTV.**
The airborne platform: The system is currently mounted on a Hughes 500 helicopter.[2] The helicopter and the system are depicted in figure 2.

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[2] A dedicated VIGILANTE helicopter has been constructed, and will be used in later stages of the project. The algorithms are constructed for this helicopter, assuming that the mirror is looking out to the right. However, on the Hughes 500 helicopter it was necessary to mount the system looking out to the left side. Therefore there are inconsistencies between pictures and the text.
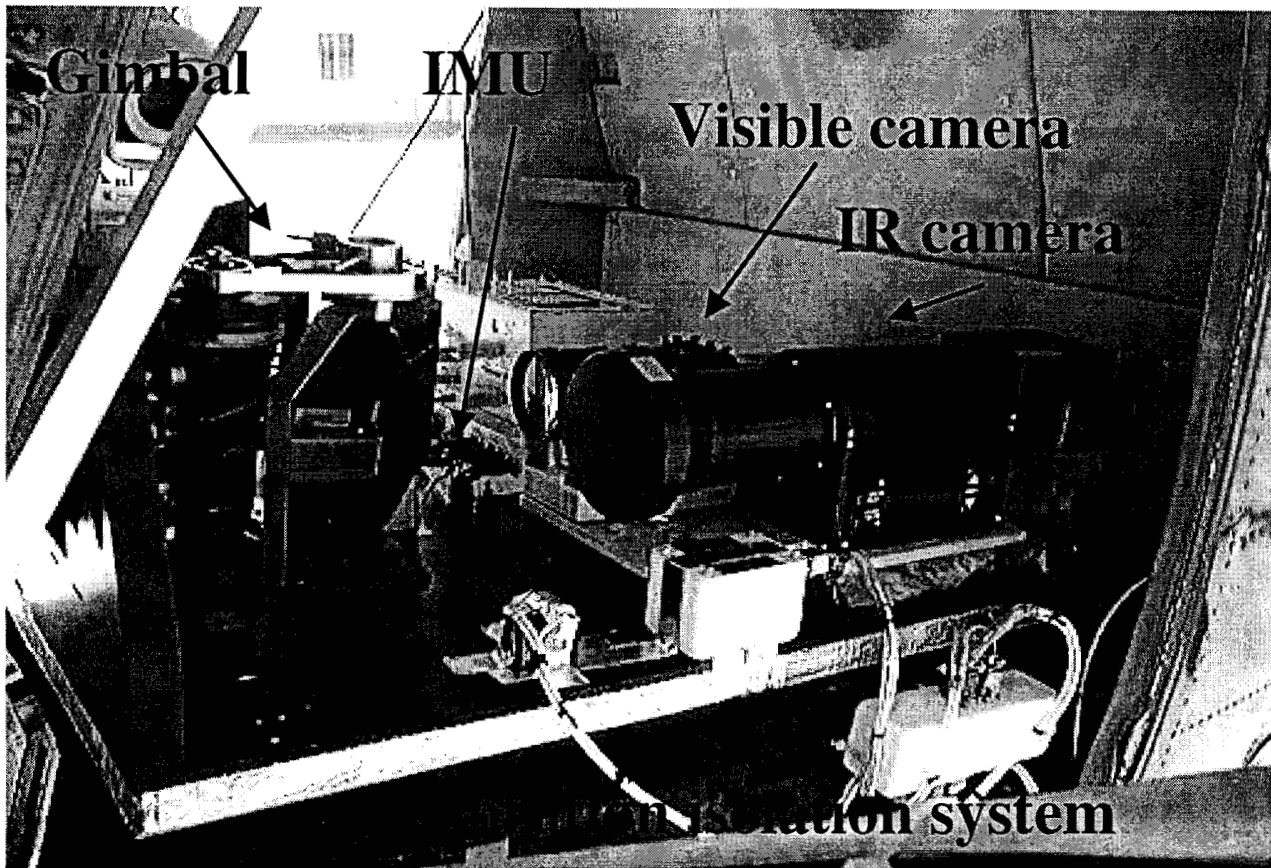
**Figure 2. A) The VIGIL helicopter. B) Close up of the cargo bay in the helicopter with the camera platform.**

As shown in figure 2, the VIGILANTE system consists of many sub-systems. In figure 3, a sketch of the system is shown. The rest of this section will describe the subsystems in details.
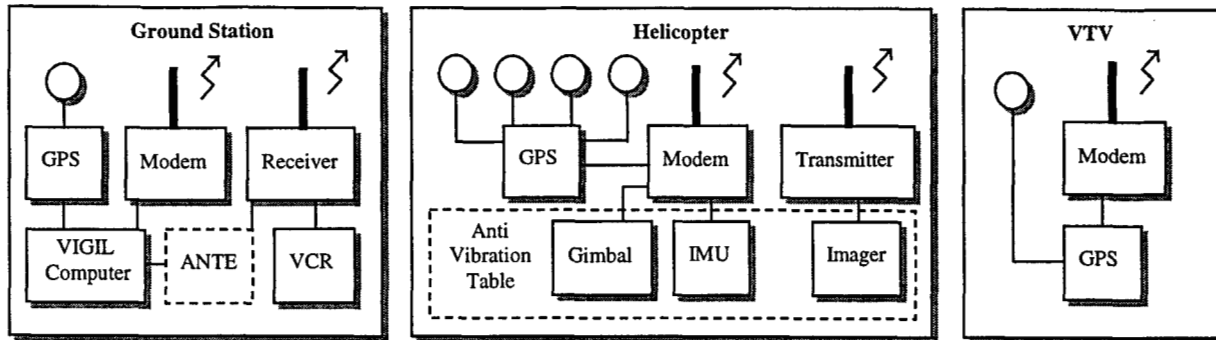


**Figure 3. Block diagram of the VIGILANTE system.**

QUANTUM WELL INFRARED PHOTO DETECTOR (QWIP) is a 256x256-pixel, real-time (30 to 120 Hz) IR sensor array. QWIP is a major advance compared to state-of-the-art HgCdTe sensors. The sensor has an 8 to 9 μm central wavelength detection capability with a 1 μm full width at half maximum, and the design uses a random reflector on each pixel to maximize light trapping. The QWIP sensors are based on GaAs.

VISIBLE CAMERA: A color Cohu CCD 768 x 494 pixel camera with is used. The camera is mounted with a Fujinon 300-mm zoom lens. In near future, the CCD camera will be replaced with an active pixel sensor camera.

VIBRATION ISOLATION SYSTEM: The Mechanical Engineering Department, University of Maryland has built an active/passive two stage vibration isolation control system for the project. The system operates on passive air mounts arranged in series with another stage of active electromagnetic actuators. The active stage is used to isolate the base excitation from the intermediate platform whose vibration is isolated from the primary system by the passive stage. The vibration isolation control system is broken into two parts. The first part is the two stage vibration isolation control box and the other is the control computer. The vibration isolation box is made of a composite material and contains the actuators, passive isolation, accelerometers and rate triad. The control computer contains the executable code, which logs the data and controls the I/O. There are two modes of operation for the system. The first mode is a continuous operation mode that isolates the optical bench with S/W controlled gain parameters, which have been optimized for a specific camera configuration. The other mode of operation is the data acquisition mode where the computer logs the output of the accelerometer and rate triads. Under most conditions, the vibration bench reduces vibration-related acceleration by a factor of ten.

TWO AXES GYRO-STABILIZED GIMBALED MIRROR: The VIGILANTE Gimbal is a two-axis gyro stabilized gimbal mirror constructed by Fraser-Volpe. The gimbal system consists of the gimbal electromechanical device and support electronics. The gimbal has an inner (horizontal) and outer (vertical) axis. The inner axis moves from -20 to +52 degrees and the outer axis moves +/- 45 degrees. The gimbal has two modes of operation: in position mode the mirror moves to the commanded position, in the rate mode the mirror slews at the command rate. The gimbal has RS 232 control and interfaces to the telemetry system for command and data. The gimbal position is read out and transmitted to the ground station at 20 Hz.

TELEMETRY SYSTEM: The VIGILANTE Telemetry system consists of three subsystems, as shown in figure 3. The first subsystem is the Ground Station, which receives all the data from the helicopter and the VTV. The second subsystem is the helicopter telemetry system consisting of two video down link channels (only one is shown in figure 3), command and data facilitating system, an attitude GPS system and an IMU. The third subsystem is the GPS system on the VTV.

- The airborne telemetry subsystem for the VIGILANTE helicopter is comprised of: Two video transmitters (one is depicted in figure 3) that sends the images from the camera platform at 2.35-2.45 GHz down for ground-based recording and processing. A Communication Router (CR) distributes the commands from the ground to the airborne instrumentation and returns the GPS, Inertial Measurement Unit (IMU) and Gimbal data to the ground station. Finally, the Attitude GPS and the IMU provide aircraft position, attitude, velocities, accelerations and roll rates to the ground station. The CR is a Motorola-based processor that receives commands from the ground and sends the data back at 57.6 Kbaud. The CR contains a 900MHz Freewave modem that sends and receives the data. The Attitude GPS system consists of a Pentium computer and 4 GPS receivers. The Attitude GPS system collects the GPS data from the 4

antennas, applies the received differential correction from the ground station and calculates a 4-antenna attitude solution (note the GPS antennas on figure 2). It then transforms the attitude solution from the GPS antenna reference frame to the aircraft reference frame. The attitude system then sends the attitude (pitch, yaw and roll), position of the aircraft (north, east, and altitude), velocities (north, east and up) and the GPS time to the ground control station. The Inertial Measurement Unit (IMU) is located on the optical bench so it is vibration isolated. The IMU transmits the accelerations and the roll rates in three axes through the CR at 50Hz.

• The ground station receives GPS data from a GPS antenna. It calculates the differential corrections and sends that information to the VTV and the helicopter. The ground station receives all the data from the aircraft and the VTV and sends it to VIGIL computer. The ground station contains two 57.6 Kbaud freewave modems and antennas, one for the VTV and the other for the aircraft command and data.

• The VTV hardware consists of a GPS antenna/receiver and a freewave modem/antenna to receive the differential corrections and to send the position and velocity data to the ground station. The VTV calculates the latitude, longitude and altitude as well as the velocities east, north and up and transmits them to the ground station at 10Hz. The ground station calculates VTV relative position with respect to the ground station.

# 3. ALGORITHMS

The algorithms will evolve through two phases: In the early phases of the project, they will point the gimbal mirror toward the target, exclusively based on GPS information. The resulting acquired images will be used for training and evaluation of the ANTE recognition processor. Later in the project, the ANTE recognition processor will be included in a closed loop. Based solely on imagery, ANTE commands the gimbal mirror without GPS information to demonstrate real time image processing real time capabilities. This paper will exclusively deal with pointing based on GPS information.

VIGIL's algorithms are based on four different coordinate systems (CS):

• The Ground Station Coordinate System (Ground-CS). The origin of the GROUND-CS is defined in the WGS-84[3] system. The geographical position of the GROUND-CS origin is irrelevant to VIGILANTE, as only the relative position of the helicopter and the VTV are important. The GROUND-CS is a Cartesian (flat earth) right hand coordinate system. The axes are defined as follows: The X-axis is pointing toward North. The Y-axis is pointing toward East and the Z-axis is pointing downwards. The units are in meters. Both the VTV and the helicopter positions are given in this coordinate system.

• The Helicopter body based CS (Helicopter-CS) is a right hand coordinate system. The origin is defined as being the right of the 4 GPS antennas on the helicopter. The X-axis is pointing forward on the helicopter. The Y-axis is pointing to the right (seen from above), and Z-axis is pointing downwards. The units are in meters. The IMU is aligned with the helicopter CS.

• The camera coordinate system (Camera-CS) is a right hand coordinate system. The origin is at the intersection of the optical axis and the CCD chip. The Z-axis is pointing backwards on the helicopter towards the gimbal mirror. The X-axis is pointing to the left (seen from above) and Y-axis is pointing down. The units are in meters.

• The gimbal-based coordinate system (Gimbal-CS) is a right hand coordinate system referring to the optical axis caused by the Gimbal mirror. The origin of the Gimbal-CS is at the center of the Gimbal mirror. The Gimbal-CS is defined as the CAMERA-CS translated to the Gimbal mirror center, and rotated $\phi$ degrees (right hand positive) around the Camera-CS z-axis. Successively the CS is rotated $\varphi$ degrees (right hand positive) around the new y-axis. The units are in meters.

In figure 4 a sketch of the helicopter and the CS's is shown.
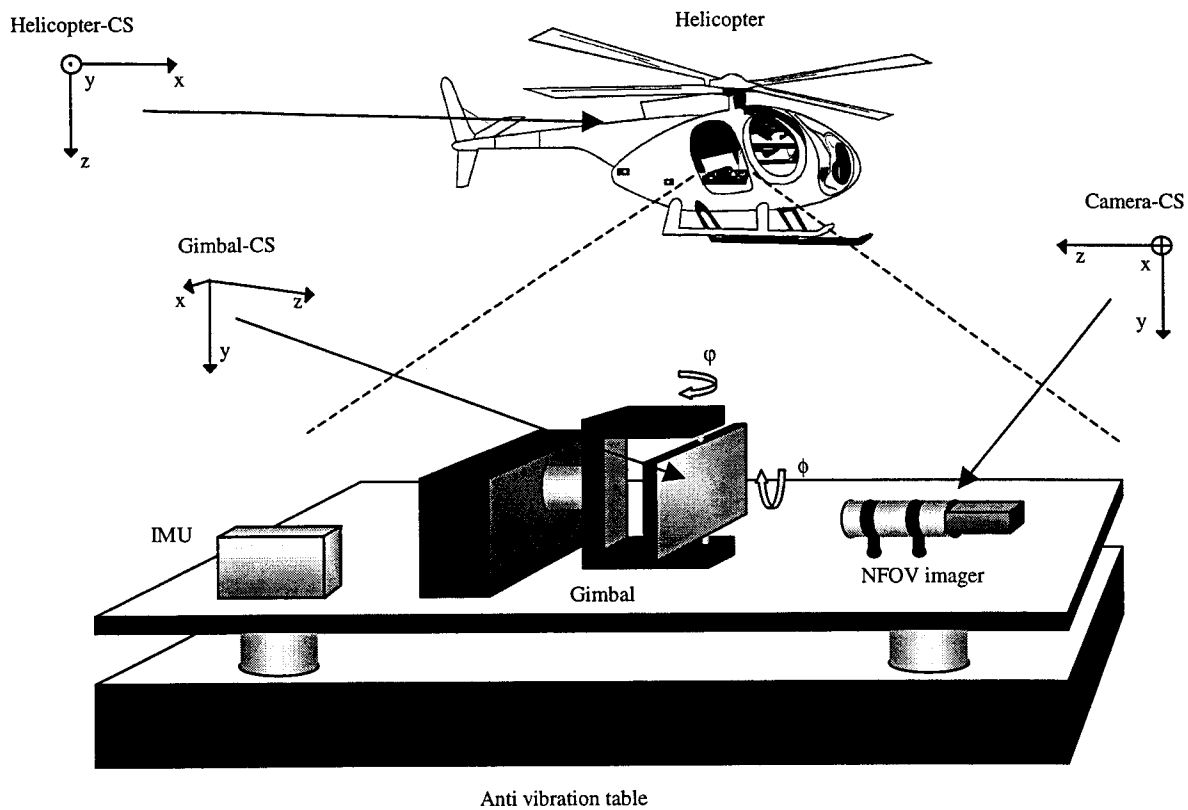
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[3] World Geodetic System 1984

**Figure 4. Sketch of the VIGIL helicopter, with its different coordinate system.**

Based on the CSs, it is now possible to describe the sequence of translations and rotations required for calculating the gimbal rates [7]. The algorithm is shown in figure 5.
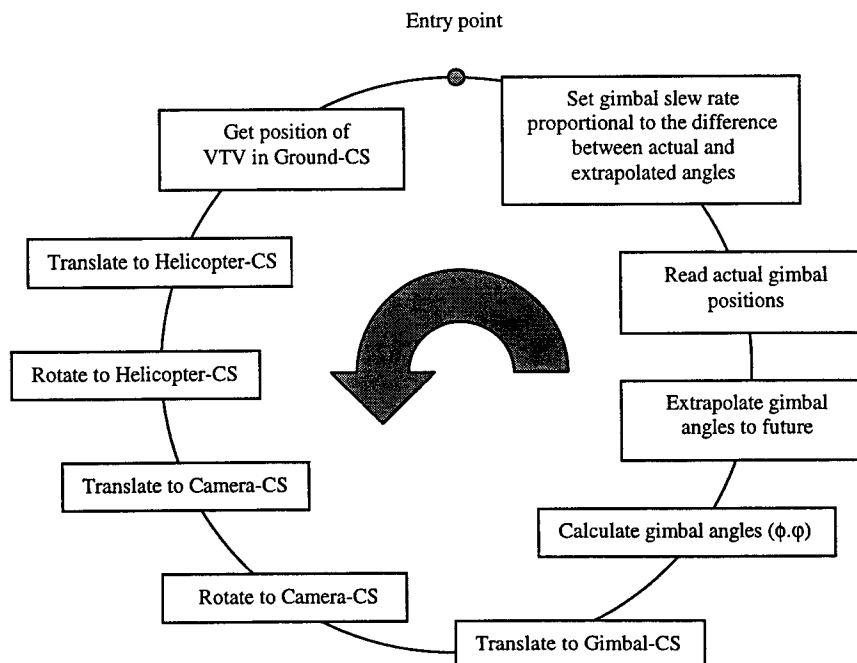


**Figure 5. The gimbal pointing algorithm. The algorithm calculates gimbal rates. The rate is proportional to the error, in the control-loop.**

The attitude of the helicopter is a combination of IMU and GPS attitude data that is updated continuously. This is because the GPS attitude has proven to be unreliable, and therefore the attitude system was made redundant by utilizing an IMU. The algorithm for calculating the attitude is sketched in figure 6.
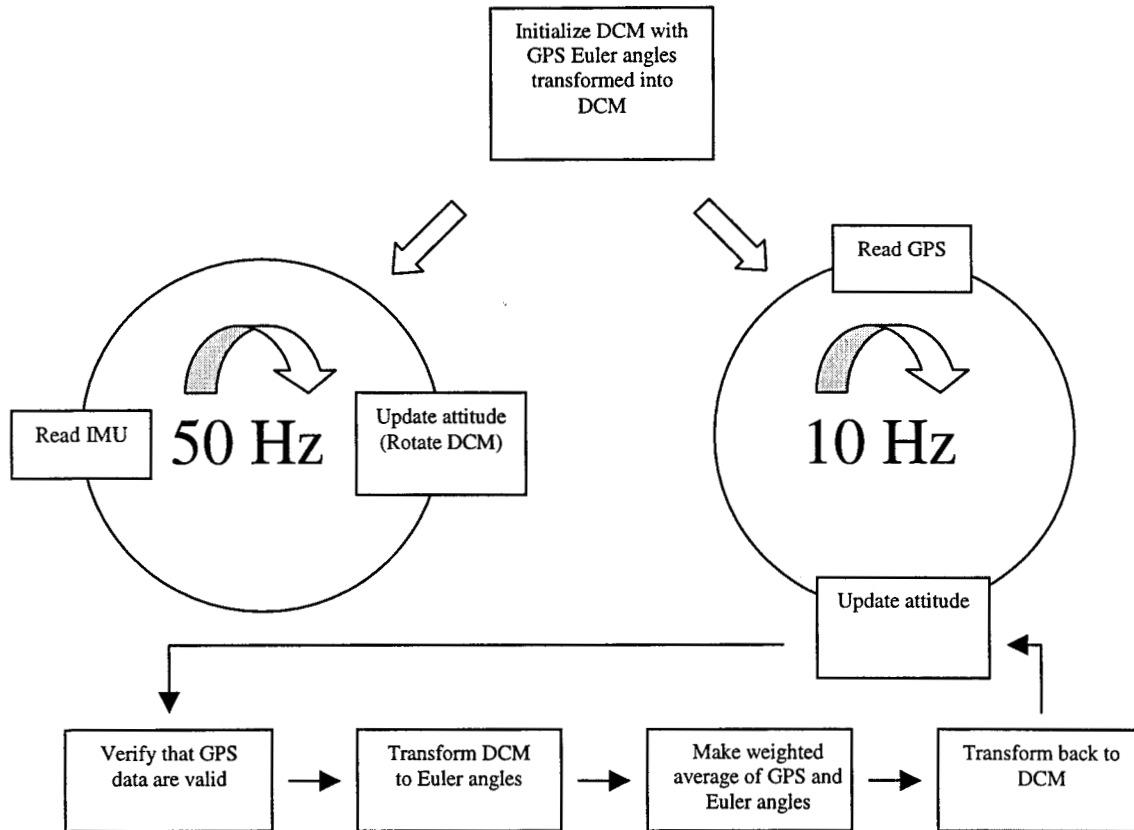


**Figure 6. Algorithm for updating the attitude (DCM = Direction cosine matrix).**


## 4. ALIGNMENT

Unfortunately, there are uncertainties in mechanical mountings, both position uncertainties and rotation uncertainties. The position uncertainty on the helicopter due to inaccurate measurements or mountings is estimated to be on the order of centimeters. Assuming that the target is several hundred meters away from the helicopter, these uncertainties can be neglected. However, there are 3 rotational uncertainties that can not be neglected:

- Rotation from Ground-CS to the GPS antenna plane is very accurate. However, the consecutive rotation to the Helicopter-CS as described in "2. DESCRIPTION OF THE VIGIL SYSTEM" is based on a rotation provided by the user. This rotation are found using a compass and leveler etc. It is estimated that the user, trying to measure this rotation could introduce an error of several degrees in each axis.

- The camera mounts and camera boxes are not precision mounts. It is estimated that there may be several degrees of error in each axis.

- The commanded gimbal angles may have an offset; i.e. 0 degrees may not be pointing orthogonal to the helicopter. It is estimated that this angle may have several degrees of error in each axis.

A realistic model of the rotations (translations not included in this model) that the VTV position undergoes is sketched in figure 7.
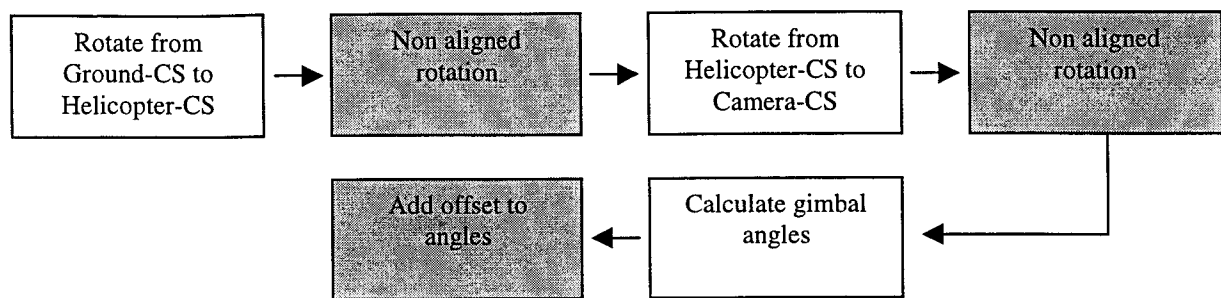
**Figure 7. A realistic model of coordinate rotations, 8 degrees of freedom.**

There are at least 8 unknown angles in this model, some with values of several degrees. It would be a very cumbersome procedure to determine and correct all these angles. Besides, the configuration of the helicopter changes often, so a calibration procedure that only takes minutes is absolutely necessary. Hence, the following approximation has been made for making an easy calibration procedure: All uncertainty rotations are collected in one single calibration rotation, which is supposed to counter rotate the uncertainties. This is depicted in figure 8.
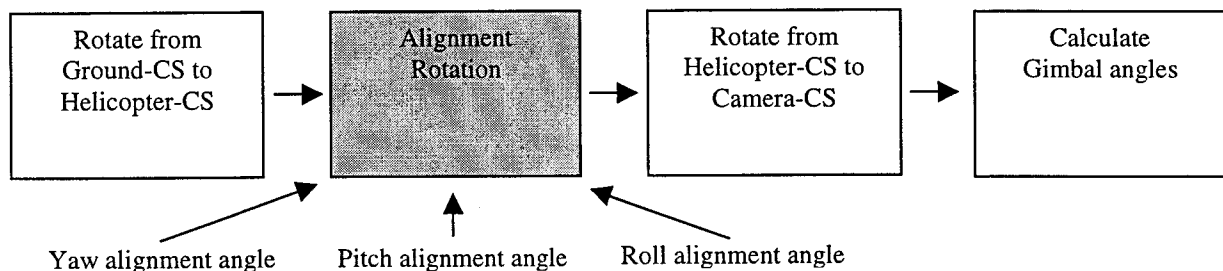


**Figure 8. An approximation of the coordinate rotations, 3 degrees of freedom.**

The procedure for calibration is then as following. The tracking algorithm as displayed in figure 5-6 is initiated. The VTV is placed approximately orthogonal to the helicopter (by eyeballing). Most likely the cameras are not pointed toward the VTV. There are then buttons to adjust the calibration angles interactively until the VTV is in the center of the field of view. This procedure takes only a few minutes. It is estimated that the error introduced by this procedure is a fraction of a degree, which is acceptable for the experiment.

## 5. EXPERIMENTAL RESULTS

The VIGIL system has been debugged and tested at the Flight Research Inc., Mojave airport, CA. Initially the noise of a static scene is considered. This is also known as the noise equivalent angle (NEA) of the system.

**Position error on the VTV and the helicopter:** The VTV and the helicopter position are differential GPS positions at 10Hz. In figure 9, the north/altitude of the VTV position is displayed for a non-moving VTV. It is estimated that north/east noise (RMS) is less than a meter for the VTV and helicopter, and that the altitude noise (RMS) is a couple of meters for both the helicopter and the VTV. It is expected that the noise would be larger in altitude due to the satellite geometry.
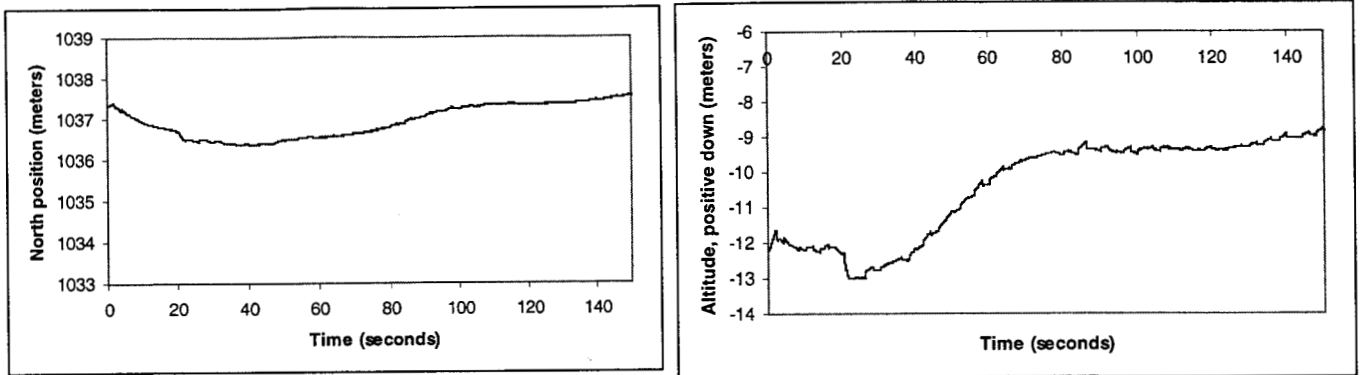
**Figure 9. The VTV position of North and Altitude. The RMS noise is 0.4 and 1.4 meters.**

**Attitude noise from the GPS system.** The attitude of the helicopter is calculated at 10 Hz and based on updates from the 4 GPS antennas (shown in figure 2). Figure 10 shows the raw yaw and roll output of the GPS attitude. The noise (RMS) is significant lower than a degree. The roll angle is noisier than the pitch/heading angle because of the shorter baseline.
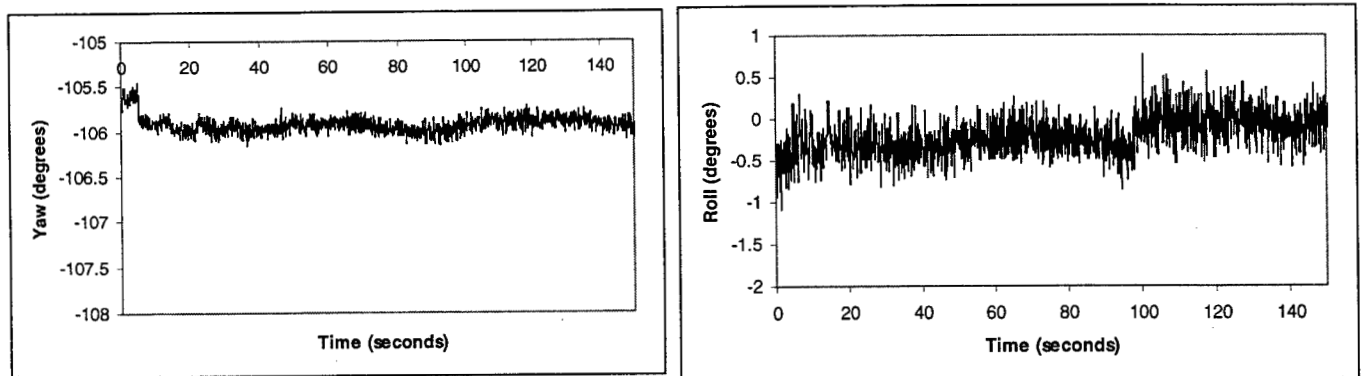


**Figure 10. The raw yaw and roll attitude from the GPS. The RMS for yaw is 0.09 degrees and for roll is 0.24 degrees.**

Unfortunately, the GPS attitude is not very stable. Hence, it is backed up by an IMU that is being integrated with 50 Hz. Hence, when the GPS does not supply an attitude; the IMU supplies the attitude. The algorithm was shown in figure 6. To illustrate the superiority of this approach, the raw yaw GPS attitude of the helicopter is shown together with the combined yaw attitude for a helicopter flight in figure 11.
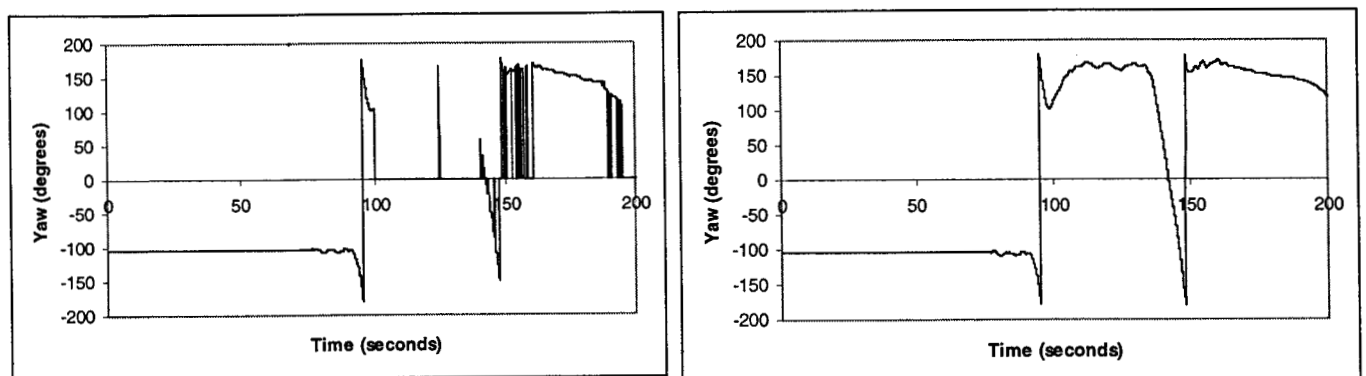


**Figure 11, The raw yaw GPS attitude and the combined attitude. The jump from –180 to 180 degrees occurs crossing south. GPS is 0 degrees when no valid attitude exists.**

All noise contributions are included in the system NEA. This is equivalent to the noise on the gimbal angles. The two gimbal angles are shown in figure 12. It is noticed that the outer gimbal angle is noisier than the inner gimbal angle. This is because of the higher noise on the roll angle and the altitude.
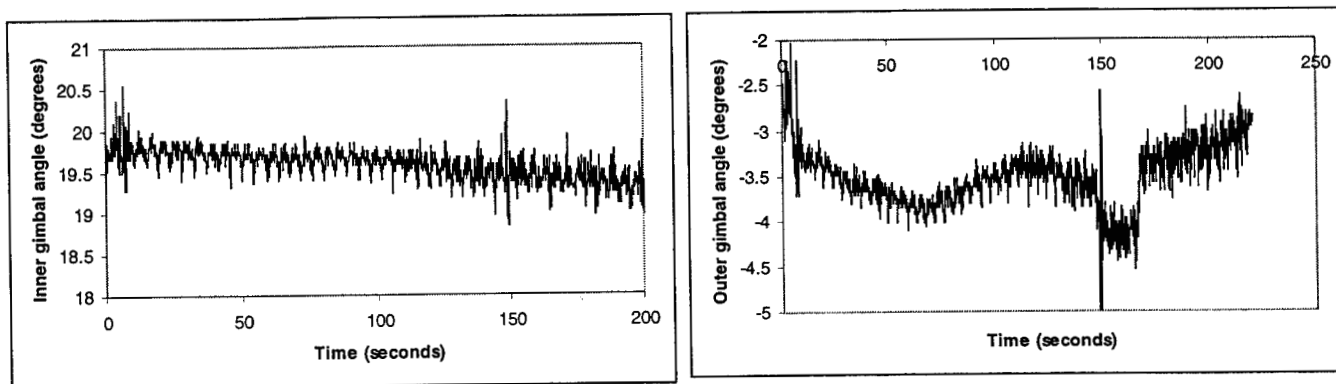


**Figure 12. The gimbal angles. The target distance is approximately 830 meters. The RMS noise is 0.20 degree for inner axis (horizontal) and 0.43 degrees for outer axis (vertical). There is a noise spike on the outer angle. It is observed that there is a periodic noise component. This will be analyzed further in the near future, but it is believed to be a resonance frequency of the optical bench.**

Unfortunately, the NEA is only a part of the total pointing error budget. When things are moving, additional errors are introduced. At this early stage of the project it is impossible to make a complete error budget. However, a qualitative description of the additional errors terms are given below:

- Nonlinearity due to collecting all alignment rotations in one alignment rotation: It is not mathematically correct to merge different rotations with different origins into the same rotation. This will introduce an error. It is estimated that this error is less than one degree.

- Flexing in the fuselage of the helicopter: During calibration, the helicopter is on the ground and the skids are carrying the weight of the helicopter. In flight, the rotor pulls the weight of the helicopter. This generates some flexing in the fuselage of the helicopter. This could amount to one degree.

- Propagation delay: There is a propagation delay in the radio modem at approximately 30 milliseconds. This means that GPS positions are old when they are received and, once the new gimbal angles are calculated it will take another 30 milliseconds before they reach the gimbal. This effect is somewhat mitigated by extrapolating the gimbal angles to the future. This effect is only significant when the VTV has high angular accelerations.

- Limited sampling frequencies: All signals are sampled. IMU is 50 Hz, GPS is 10Hz, VTV position is 10 Hz and Gimbal position is 20 Hz. This limited sampling frequency will introduce an error when things are moving.

It has not yet been possible to make a thorough assessment of the equipment. However, during the first flights the equipment worked fine. The best way to illustrate the system capabilities is to show a series of selected pictures that was acquired of a prototype VTV, with the VIGIL helicopter on the ground. The images are shown in figure 13.
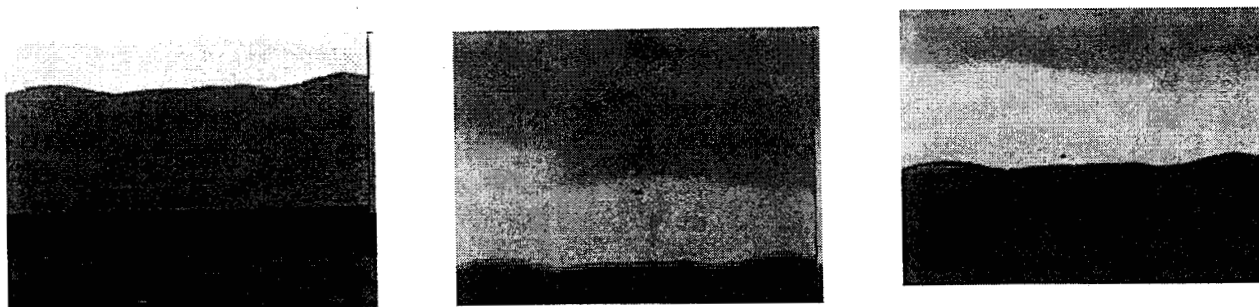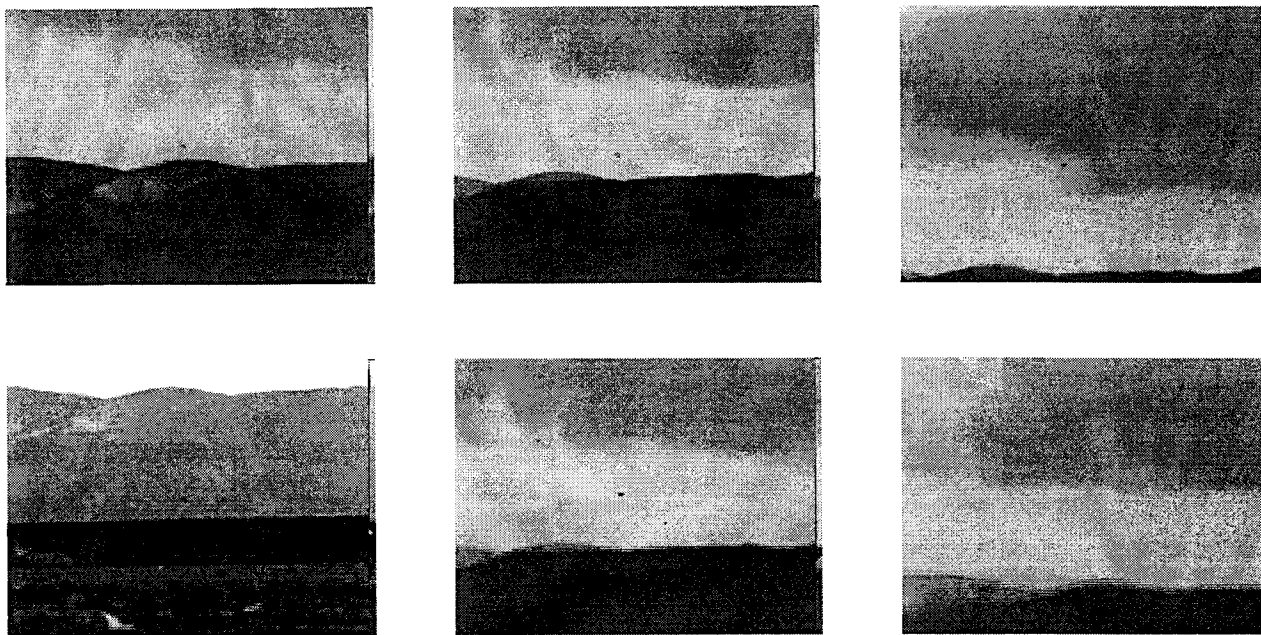
**Figure 13. Selected images from a tracking video of the VTV. The images shown are very preliminary, and a radio-controlled helicopter on 1 m was used as VTV. The distance was approximately 830 m. The helicopter is the black spot in the center of the images. The field of view of the camera was approximately 3 degrees.**

# 6. SUMMARY

This paper has been describing the VIGILANTE system. The flying target is equipped with GPS and radio modem. The helicopter is equipped with an active vibration isolated bench and a radio modem. On the bench, an IMU, the IR and visible camera and the gimbal are mounted. Outside the helicopter fuselage 4 GPS antennas are mounted. These provide a 4-antenna GPS attitude solution.

There are defined four coordinate systems, a ground based CS, a helicopter based CS, a camera based CS and a gimbal mirror based CS. The algorithms consist of successive coordinate translations and rotations of the target coordinates though the coordinate systems until the gimbal angles are calculated. The gimbal is finally commanded to a rate proportionally to the difference between the present mirror position and the calculated gimbal mirror position. The attitude GPS has proven to be unreliable, and is therefore backed up by an IMU.

There are multiple mechanical misalignment sources on the helicopter. Positional errors are small compared to the distance to the target, that they are ignored. All rotational uncertainties are collected in one alignment rotation. It is possible to adjust the Euler angles of this alignment rotation iterative, until the target is at the boresight. This procedure only takes a few minutes and introduces an insignificant error.

The system has been tested in the Mojave dessert. The static noise of the system is a fraction of a degree. The noise is larger when both the helicopter and the VTV are airborne. With a target distance of approximately x meters and a field of view of x degrees, the VTV was in the field of view at all times. The system has proven to be an essential component to test new sensors and evaluate and train ATR algorithms with realistic scenarios.

# 7. ACKNOWLEDGMENT

References herein to any specific commercial product, process, or service by tradename, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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